

# DESIGN AND CFD ANALYSIS OF FOOD DRYER USING SOLAR FLAT PLATE COLLECTOR AND EXHAUST GAS WITH FINNED COPPER TUBES

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## ABSTRACT

*To remove moisture direct, indirect mode solar drying methods are available. Indirect method, the crop is directly exposed to solar radiation. But in the case of incident method crop is placed in the closed system and solar radiation is absorbed by some transparent surface – usually, a solar collector where it is converted into heat by refraction in the system. But this method is applicable on sunny days only. So the exhaust gas was used as heat source for drying with the help of copper heat exchangers irrespective of seasons. This method has the capability of reducing the drying time by up to 50 percent compared to traditional drying. In order to obtain the best results, current work focuses on modeling and analysis of solar food dryer attached with the flat plate collector and exhaust gas heat exchanger. CFD Analysis of food dryer containing exhaust pipe heat exchanger with and without fins is carried out. The results are compared and the best heat transfer model is recommended. From the theoretical, Numerical and experimental validation, it was found that the output temperature of the Flat plate collector whose overall efficiency of 5.7 was compared in different cases. There was a gradual increase in output temperature when exhaust pipe was added and further step increase when exhaust pipe with fins was added. As a result of increased output temperature and moisture numerical rate was increased.*

**KEYWORDS:** Solar Crop Dryer, Exhaust Gas Heat Exchangers, Flat Plate Collector, Fins & CFD Analysis

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## 1. INTRODUCTION

The major objective in drying agricultural products is the reduction of the moisture content to a level called as equilibrium moisture content, which allows safe storage over an extended period. Moisture removal from food products prevents the growth and reproduction of microorganisms which cause decay. Drying the grapes and making raisins form different types of grapes has good business value. Drying technique which is used has lots of impact on the quality of the product. The most common drying method is sun drying, which is traditionally practiced in many countries. This traditional method has the advantages of simplicity and less initial investment. However, it requires large areas, high labor costs and the drying process completes in 15–20 days which is uneconomical. In order to improve the quality, traditional sun drying techniques can be replaced by industrial drying methods such as hot-air mechanical and solar drying. It is reported in the literature that work on solar and hot-air drying of agricultural food products have been carried out by many researchers.

[1] A design of double-pass solar drier (DPSD) by using forced convection, natural convection solar drier (CD) and traditional open-sun drying (OSD) were designed for drying of bamboo shoots in central Vietnam. [2] The design and analysis of cylindrical section solar drying system and the performance was done. The maximum and minimum values of the average thermal efficiency of the solar air with the solar air collector obtained at air flow rates were 25.64% of 0.0675 kg/s, 18.63% at air flow rate of 0.0405 kg/s. the initial moisture content of beans was 70% and the final 14% when the air flow rate of 0.0540kg/s and 20% d. b at an air flow rate of 0.0765 kg/s. [3] Direct natural convection star appliance to dry foodstuff within the geographical region was designed and fabricated. The climate thought-about space of Warri (lat. 5°30', long. 5°41'), Nigeria. An epitome of the appliance thus designed was invented with minimum collector space of 1.08 m<sup>2</sup>. [4] Kinetics of apricot skinny layer drying during a forced convection mixed and indirect mode cupboard solar drier with (total collector expanse of 4m<sup>2</sup> and total receptacle expanse of 0.7m<sup>2</sup>) was used. Victimization multiple correlation analysis, the impact of drying operative conditions (air temperature and velocity) on the model constants and coefficients are determined.

[5] The solar radiation vented cupboard appliance was designed, made and tested in the Federal Republic of Nigeria on latitude 7.5° N. The system potency accumulated because the air rate through the system accumulated. At the testing amount, the typical air rate and daylight efficiencies through the star appliance was 1.62 m/s and 46.7% severally. [6] A greenhouse sort star appliance for small-scale dried food industries was developed and disseminated. The appliance consists of a parabolic roof structure lined with polycarbonate sheets on a concrete floor. In this system drying of osmotically dehydrated tomato was conjointly developed by using a system of differential equations describing heat and wet transfers. [7] The appliance model was evaluated by victimization commercially accessible procedure fluid dynamic (CFD) code so as to grasp the warmth and mass transfer within the appliance. Natural convection was the sole mode of warmth transportation plan of getting an easy style. A biomass burner was integrated into the star appliance designed to accommodate the result of low buoyancy found in natural convection driers. [8] A numerical simulation of the airflow within a hybrid solar-electrical drier, employing a business CFD package was presented. With prescribed temperatures and velocities, the model predicts the behavior of the air flow within the device.

The objective of the paper is to do theoretical, numerical and experimental validation in comparing the efficiency of the solar crop dryer with exhaust gas heat exchanger with and without fins.

## 2. THEORETICAL ANALYSIS:

The most important factor affecting the moisture content of food particles in a solar crop drier is the intensity of solar radiation, which depends upon the geographical position of the place, season of the year and time of the day. Typically, the temperature changes in the cabin and the moisture content is evaluated as follows.

### 2.1 Design Calculations

To obtain the size of the dryer and design calculation, the design conditions applicable to Kurnool is required. From the conditions, assumptions, and relationships, the values of the design parameters were calculated.

#### Moisture to be Removed

The amount of wetness to be aloof from a given amount of a carrot slices to bring the wetness content to a secure storage level in a very given time.

The amount of moisture to be removed from the product,  $m_w$ , in kg was calculated using the equation

$$m_w = m_p(M_i - M_f) / (100 - M_f) \quad (1)$$

### Equilibrium or Final Relative Humidity

By using sorption isotherms the Equilibrium or final relative humidity were calculated and an equation for crop given as follows

$$a_w = 1 - \exp[-\exp(0.914 + 0.5639 \ln M)] \quad (2)$$

$$a_w = ERH/100 \quad (3)$$

### Quantity of Heat Needed to Evaporate the Water (H<sub>2</sub>O)

To evaporate the water (H<sub>2</sub>O) the required heat quantity would be

$$Q = m_w \times h_{fg} \quad (4)$$

The given equation is used to calculate the latent heat of vaporization, and the equation can be

$$h_{fg} = 4.186 \times 10^3 (597 - 0.56(T_{pr})) \quad (5)$$

### Air Vents Dimensions

By dividing the volumetric air flow rate by the wind speed the calculated air vent would be

$$A_v = V_a / V_w \quad (6)$$

the width of the air vent is given by

$$B_v = A_v / L_v \quad (7)$$

### Required Pressure

$$\text{Velocity} = V_a / A$$

The pressure difference across the carrot slices bed will be solely due to the density difference between the hot air inside the dryer and ambient air.

Air pressure can be determined by the equation

$$P = 0.00308 g(T_i - T_{am}) H \quad (8)$$

The prototype of solar dryer was sized to have a minimum area of 1 m<sup>2</sup> to used in experimental drying tests.

### 2.2 Additional Information about Kurnool, Andhra Pradesh, India in March

Average temperature : 35°C

Relative Humidity : 42%

At average temp and RH the values obtained from psychometric chart are

Initial enthalpy : 61.28 KJ/Kg

Humidity ratio : 0.01218

### 2.3 FIN Calculations

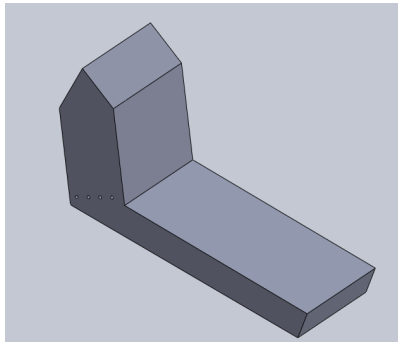
The heat transfer from n-fins is given by

$$Q = n \cdot k \cdot A \cdot m \cdot (T_{out} - T_{in}) \cdot \tanh ml \quad (9)$$

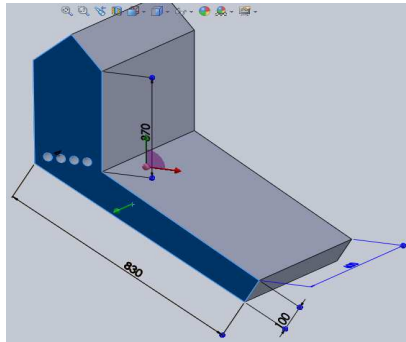
## 3. NUMERICAL ANALYSIS:

### CASE:1

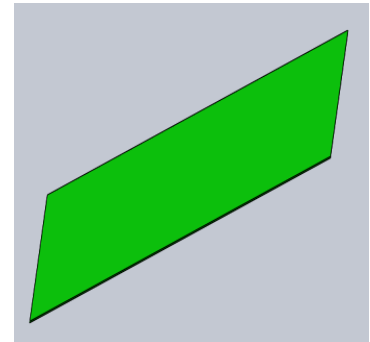
#### 3.1 Modelling of Food Dryer Without Exhaust Gas and Without Fins by Using Solidworks



**Figure 1: Model Without Exhaust and Without Fins**



**Figure 2: Drying Chamber**



**Figure 3: Glass Plate**

The above figure 1 shows the model of Food Dryer. The Food dryer has been modeled in Solid works. The dryer consists of the parts like drying chamber, glass plate and trays are arranged vertically inside the dryer are modeled and assembled as per the dimensions.

#### 3.2 Air Domain

The above figure 2 shows that air domain of Food dryer, it means that the path of fluid flow in the dryer. The hollow part dimensions of the drier are taken. From that dimensions which are represented above, the air domain has been created in Solid works and air domain had been saved in IGES file.

#### 3.3 Glass Plate

The figure 3 represents the glass plate of the food dryer which is used to allow the path flow of the fluid into the air domain with the abovementioned dimensions had been modeled in the solid works. Then the created domains had been saved into IGES file.

#### 3.4 Meshing

ANSYS ICEM CFD meshing technologies provide physics preferences that help to automate the meshing process. In the initial design Tetrahedral mesh has been generated Further refinement can then be made to the mesh to improve the accuracy of the solution. The preferences for the different Simulations are there to generate meshing. By setting physics preferences, the software adapts to more logical defaults in the meshing.

##### 3.4.1 Mesh Generation:

Meshing System : ICEM CFD 14.0

Global Element Scale Factor: 1

Mesh Type : Tetra/Mixed

Fluid Material : Air at 25<sup>0</sup>C

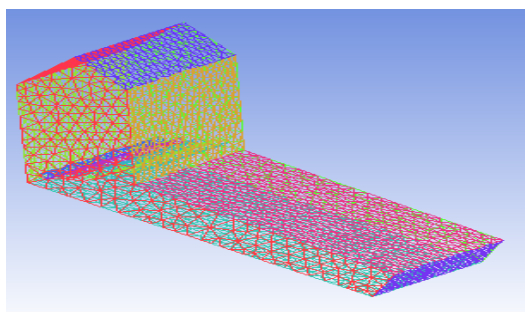
**Table 1: Mesh Details**

Domain	Nodes	Elements
Air	792	464
Glass Plate	11726	4095

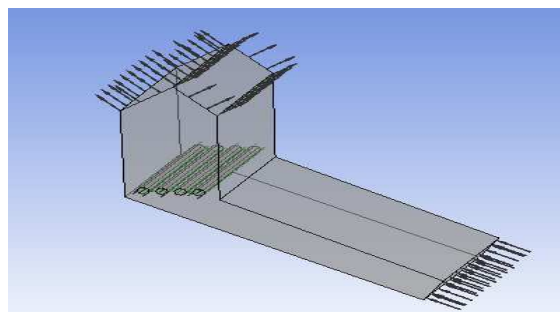
In CFD analysis air domain for the path of air flow in Chamber is created. Initially, IGES file of the air domain of Solar Crop dryer can be imported to ANSYS. The domain is meshed by using ICEMCFD with tetrahedral elements. Table 1 shows the meshed details in the air domain generated. The mesh for glass plate was created of triangular elements with element size 1 mm. Near the wall of the Drying chamber, the elements were created so as to capture boundary layers finely. Patch dependent method used for meshing. Mesh quality was above 0.3 after smoothing was applied.

### 3.5 Boundary Conditions

The below-represented figure 5 shows the model of the Food Dryer Without Exhaust gas and Without Fins, after applying all the boundary conditions. The boundaries giving in this case, are the inlet of mass flow rate in the X- direction and the pressure in the Y- direction. The heat flux is given on the Glass plate. After applying all the boundary conditions to the air domain and glass plate they are imported in Fluid Dynamics workbench of CFX 14.0. Then by using the Define run command by giving a proper number of iterations, the process had been done. After completing iterations, the post processing results are obtained for different parameters. The air flow rate has been varied from 2 to 7 kg/min.



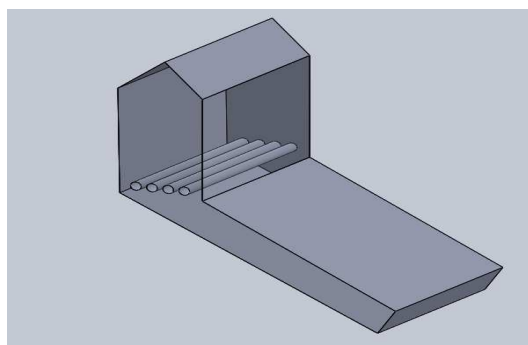
**Figure 4: Meshed Model of Drying Chamber**



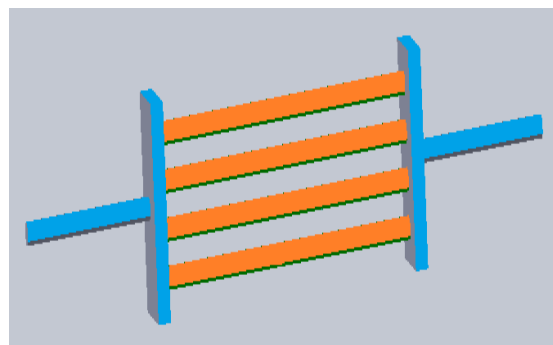
**Figure 5. Boundary Conditions**

### CASE 2:

### 3.6 Modelling of Food Dryer with Exhaust Gas and Without Fins by using Solidworks



**Figure 6: Model of Food Dryer with Exhaust Tube**



**Figure 7: Exhaust Tubes**

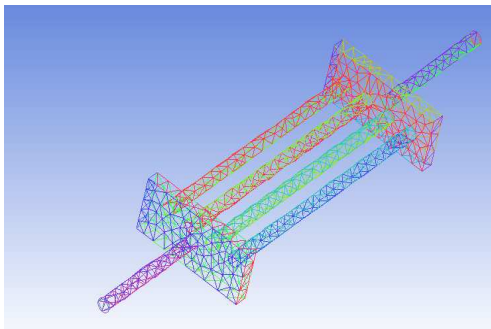
The above figure 6 shows the model of Food dryer with an exhaust tube and without fins.

### 3.7 Exhaust Tube

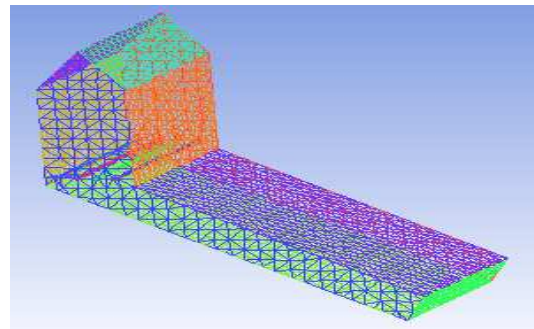
The above figure 7 shows the exhaust domain of Food dryer, it means that the path of fluid flow in drier is supplied by this exhaust tube. The hollow part dimensions of the drier are taken. From that dimensions which are represented above, the air domain has been created in Solid works and air domain had been saved in IGES file.

### 3.8 Mesh Generation

After saving the file in the STEP/IGES file, that file has been imported to ICEMCFD for the Mesh Generation. The Mesh details of the Assembly has been mentioned below



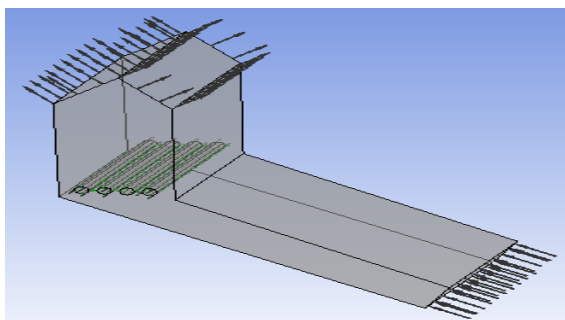
**Figure 8: Meshed Model of Exhaust Tube**



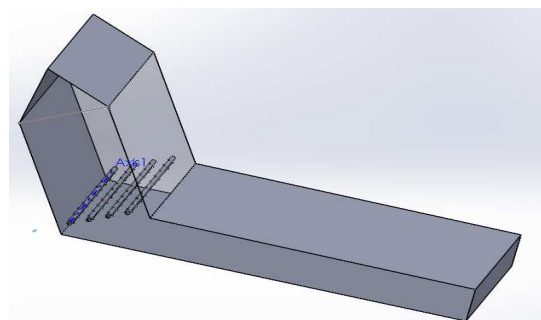
**Figure 9: Meshed Model of Food Dryer with Exhaust Tube**

Figure 8 and 9 gives the meshed details of the air domain with an exhaust pipe. The mesh was created of triangular elements with element size 1 mm. Near the wall of the solar still, the elements were created so as to capture boundary layers finely. Patch dependent method used for meshing. Mesh quality was above 0.3 after smoothing was applied.

### 3.9 Boundary Conditions



**Figure 10: Boundary Conditions**



**Figure 11: Assembly of Food Dryer with an Exhaust Tube and Copper Fins**

The above-represented figure 10 shows the model of the Food Dryer With an Exhaust gas and Without Fins, after applying all the boundary conditions.

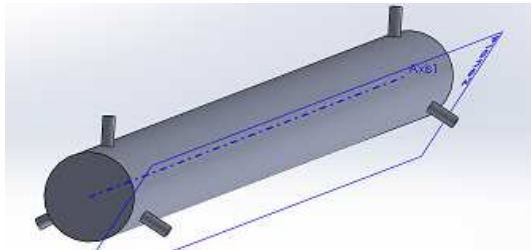


**CASE 3:**

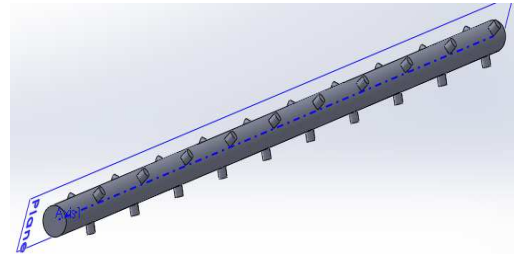
**3.10 Modelling of Food Dryer With an Exhaust Tube And With Copper Fins By Using Solidworks**

The figure 11 shows the model of Food dryer with exhaust tube and with Copper fins.

**3.11 Fins**



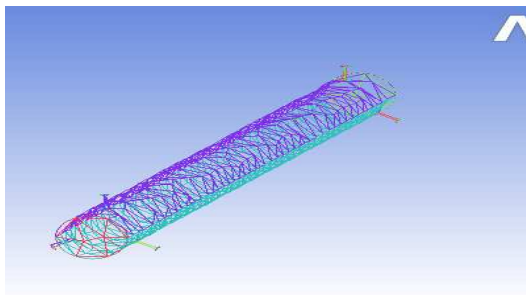
**Figure 12: Copper Tube with Single Fin**



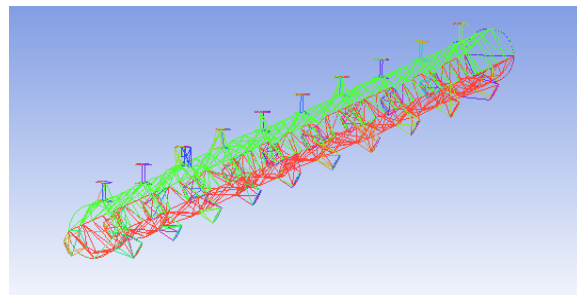
**Figure 13: Copper tube with Ten Fins**

The above figure 12 represents the arrangement of the single fin on the exhaust tube of food dryer, it means that the path of fluid flow in the dryer is supplied by this exhaust tube containing single fin, but the flow of the fluid will be less in this case. Hence we are considering the number of fins on the exhaust tube. The above figure 13 shows the Exhaust tube with ten fins, it means that the path of fluid flow in drier is supplied by this exhaust tube.

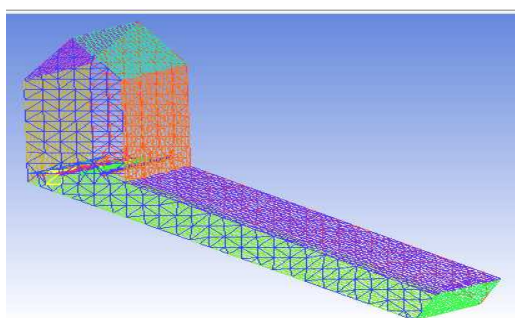
**3.12 Mesh Generation**



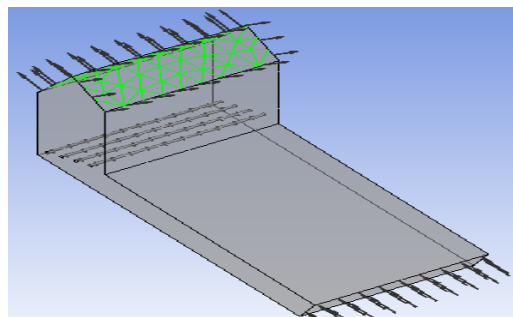
**Figure 14: Mesh of Exhaust Tube with Single Fin**



**Figure 15: Mesh of Exhaust Tube with Ten Fins**



**Figure 16: Meshed Model with Ten Fins**



**Figure 17: Boundary Conditions**

The above figure 14, 15 and 16 represents the meshed model of the exhaust pipe with a single fin and ten fins with an assembly of the Food Dryer consists of the glass plate, exhaust tube containing fins and tray inside the drying chamber

### 3.13 Boundary Conditions

Figure 17 shows the boundary condition of the food dryer when assembled with exhaust copper tube with 10 sets of fins.

## 4. EXPERIMENTAL ANALYSIS

In this experiment analysis, a forced convection Food Dryer using Solar Flat plate collector and Exhaust Gas with Finned Copper Tubes was fabricated. The system consists of a solar flat plate air collector, drying chamber, centrifugal blower, and a reversible fan. Solid, packed bed of solar regenerated with the fins was stacked at the inclined roof of the drying chamber.

Figure 18 shows the schematic of the forced convection of a solar drying system for fabrication. A single-pass, single-glazed conventional solar air collector had been used to gain useful energy from the incident solar radiation. The solar air collector was positioned towards the south at a tilt angle of  $30^0$  with the horizontal. A solar air collector and the drying chamber are connected with an insulated flexible house. The drying chamber has three trays with Net cloth (cheese cloth) and wooden frames to hold the products for drying. A reversible fan was used to draw the ambient air through the fins for its regeneration during the sunshine hours and to circulate the air inside the drying chamber during the off-sunshine hours, respectively. The air heated from the solar flat plate collector was forced through the drying trays to absorb the moisture. In this, we calculate the removal of moisture in dry basis and wet basis. To reduce the losses for the dryer an insulation material was made using 8 mm wooden plywood.



**Figure 18: Experimental Setup of Food Dryer**



**Figure 19. Copper Tubes With and Without Fins**



**Figure 20: Arrangement of the Heat Exchanger**



## 5. EXPERIMENTAL RESULTS

The Experiment is conducted on the Food dryer having solar flat plate collector with Exhaust gas and Copper finned tubes. The results are tabulated based on the design conditions and assumptions.

### 5.1 Food Dryer without Exhaust Gas and Without Fins

In this Case, the experiment is conducted for 2 hours for the Carrot as food particles. As this is a natural convection process the temperature is varying in the dryer. The values are tabulated below

**Table 2: Temperature Variation in the Dryer (Natural Convection, Carrot)**

Time(hours)	Bottom Tray $^{\circ}\text{C}$	Top Tray $^{\circ}\text{C}$	Outside Temperature $^{\circ}\text{C}$
10:00	38	37	39
10:20	39.2	40	39
10:40	41	41.5	40
11:00	42	43	41
11:20	43	44	43
11:40	44	45	43
12:00	44.5	46	44

The above table 2 shows the variation of temperature in the dryer through the solar drying process.

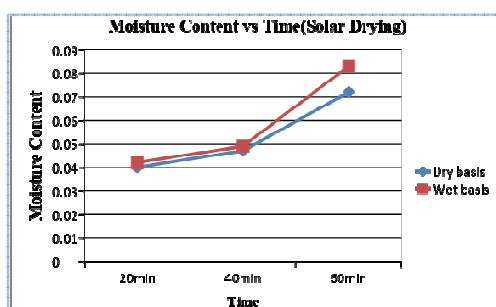
### 5.2 Food Dryer with Exhaust Gas and Without Fins

**Table 3: Temperature Variation in the Dryer (Exhaust Gas from Diesel Engine, Carrot)**

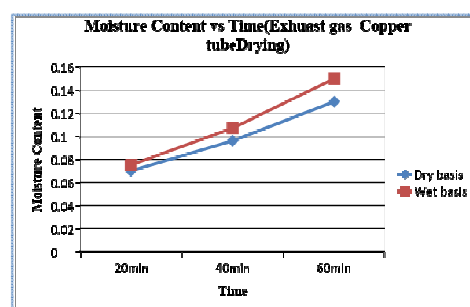
Time (hours)	Cabin Temperature $^{\circ}\text{C}$	Exhaust Tube Temperature $^{\circ}\text{C}$	Outside Temperature $^{\circ}\text{C}$
10:00	30.1	46	35
10:20	31.7	65	35
10:40	37.5	69	36
11:00	39.3	87	36
11:20	41.2	95	37
11:40	43.5	97	36
12:00	43.8	105	36

The above table 3 represents the Temperature variation in the dryer during the Exhaust Gas Drying Process. In this case, the change in temperature in the Exhaust Tube is high when compared to the Cabin and Outside temperature because of the hot gas is sent into the dryer through the Exhaust Tube.

### 5.3 Food Dryer with Exhaust Gas And With Copper Finned Tube



**Figure 21: Moisture Removal in Solar Drying Process**



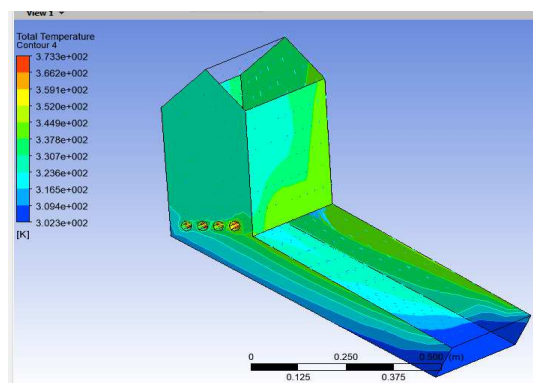
**Figure 22: Moisture Removal in Copper Tube Drying process**

The above two figures 21 and 22 shows the removal of moisture content in Solar Drying and Exhaust Gas Copper tube Process. Here it is observed that in the Exhaust gas copper tube process the removal of Moisture content is high because of the exhaust heat and the finned copper tubes are there in the Drying chamber.

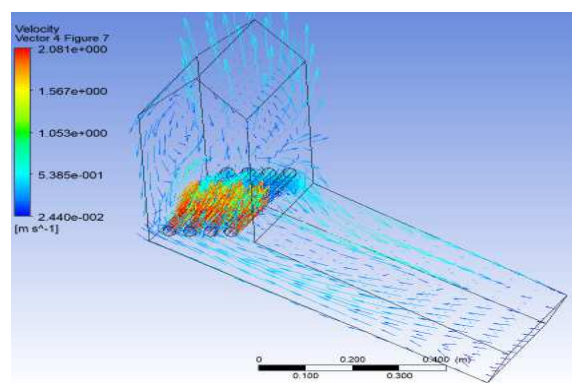
## 6. NUMERICAL RESULTS

The performance of a Solar Crop dryer depends upon the glass cover angle, a rate of heat transfer, fabrication materials, a temperature in the drying chamber and insulation thickness which could be modified for improving the performance. So Computational fluid dynamic (CFD) simulation approach is adopted to analyze the effect of Temperature variation to obtain the maximum yield. In the drying chamber, the velocity flow inside the chamber will change which is very difficult to model mathematically. The complicated thermal relationship involved in the liquid phase is accurately solved by using CFD. The numerical analysis using CFD CFX 14.0 is used to determine the temperature distribution and behavior of buoyant flow. In the present work, following the simulation methodology and utilizing the boundary conditions as mentioned in detail chapter 4, simulations were completed to obtain the following sets of results:

### 6.1 Food Dryer without Exhaust Gas and Without Fins



**Figure 23: Temperature Distribution (Solar Drying)**

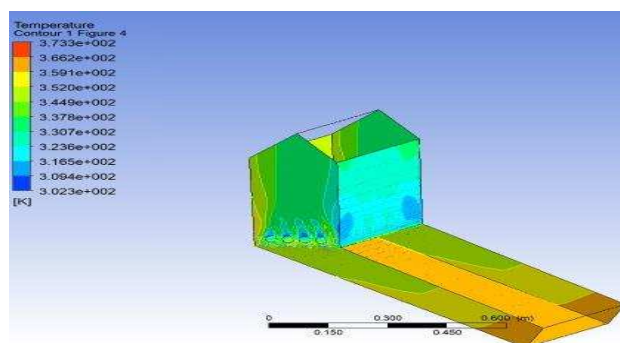


**Figure 24: Velocity Distribution in the Exhaust Domain**

The above Figure 23 shows the results of simulation runs  $25^{\circ}\text{C}$  to  $70^{\circ}\text{C}$  with the rise in intervals. The air inside the drying chamber starts warming due to heat supplied from the bottom. A temperature difference between the drying chamber and cabin temperature leads to the removal of moisture content due to the temperature source applied at the bottom and non-uniform temperature distribution is generated in the domain. Hence the maximum temperature is obtained at the bottom tray and there is variation in the temperature in the Cabin temperature. As this process is natural convection process the change in the temperature will be less and it requires more time to remove the moisture content from the Crop.

### 6.2 Food Dryer with Exhaust Gas and With Fins

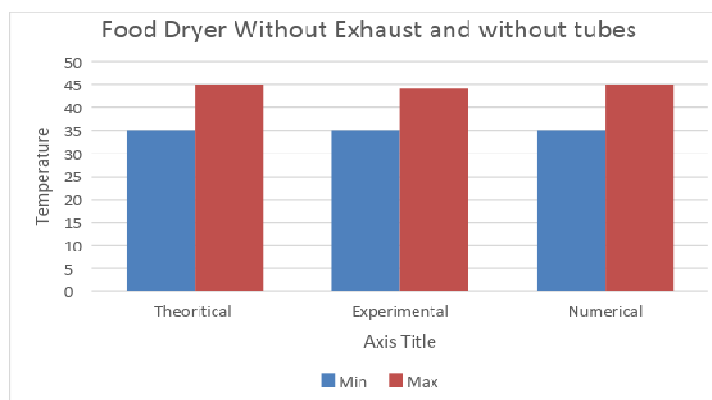
Heat transfer is due to the buoyancy force. The air flows inside the drying chamber from top to bottom in the XY direction as shown in above figure 24. The figure shows the path of air flow inside the chamber in the Air domain and Exhaust domain. Hence the flow of velocity changes takes place and the maximum velocity is obtained in the exhaust domain due to the exhaust heat supplied into the chamber.



**Figure 25: Temperature Distribution in Food Dryer (Exhaust Drying)**

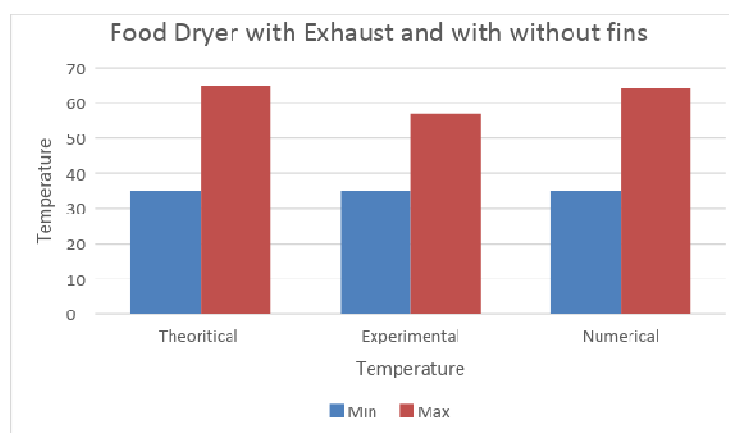
The above Figure 25 shows the results of simulation for Food dryer with exhaust gas and with fins.

## 7. COMPARISON OF RESULTS



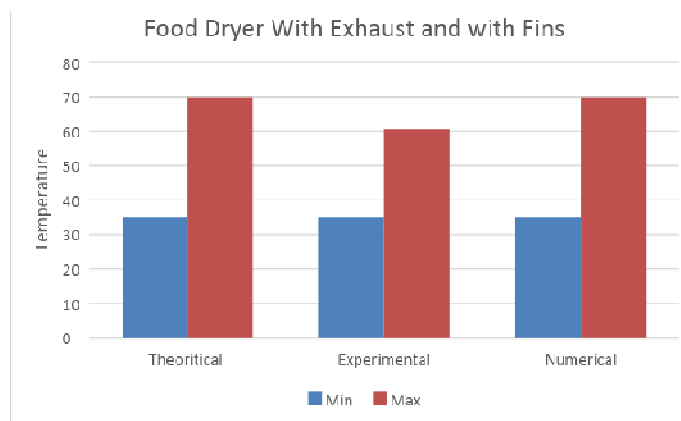
**Figure 26: Comparison of Results of Drier Without Exhaust and Without Tubes**

The above-represented Figure 26 shows the graphical data of food drier without exhaust tube and without fins. Here we concluded that the temperature in the experimental analysis is less due to the heat losses when compared to theoretical and numerical analysis.



**Figure 27: Comparison of Results of Drier With Exhaust and Without Tubes**

The above-represented Figure 27 shows the graphical data of food drier with an exhaust tube and without fins.



**Figure 28: Comparison of Results of Drier With Exhaust and With Fins**

The above-represented Figure 28 shows the graphical data of food drier with an exhaust tube and with fins.

## 8. CONCLUSIONS

In this work, a Food Dryer having Solar Flat Plate Collector with Exhaust gas and Copper Finned Tubes was modeled by using solid works and CFD analysis is carried out using ANSYS. Experimental models were used to predict the Temperature variation in the drying chamber to find the Weight loss and removal of the Moisture Content for different cases. The Conditions for the local place are used to estimate the irradiances received and to perform the Experimental Analysis. The Temperature variation is different for different cases. At last, we observed the Food Dryer with the Solar Flat Plate Collector with Exhaust Gas and Finned Copper Tube has the maximum weight loss and Moisture removal content is high in this case. The behavior of phase change and temperature distribution is observed due to heat Transfer. The temperature of Chamber obtained by CFX and the weight loss is compared with the available data. So by using these type dryers we can install at storages houses, warehouses and go down can use generator exhaust to remove moisture for preservation until next crop.

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## **NOMENCLATURE**

$m_p$  is the initial mass of product to be dried, kg;

$M_i$  is the initial moisture content, % wet basis

$M_f$  is the final moisture content, % wet basis

$a_w$ =water activity, decimal

$M$ =moisture content dry basis, kg water/kg dry solids

$Q$ =the required amount of energy, KJ

$m_w$ = mass of water, kg

$h_{fg}$  = heat of evaporation, kJ/Kg -H<sub>2</sub>O

$T_{pr}$ = product temperature in °C

$A_v$  is area of the air vent in m<sup>2</sup>,

$V_w$  is wind speed in m/s

$L_v$  is length of air vent, m,

$B_v$  is width of air vent in m.

$V_a$ = volumetric flow rate in m<sup>3</sup>/sec

$H$  = pressure head (height of the hot air column from the base of the dryer to the point of air discharge from the dryer), m;

$P$  = air pressure, Pa;

$g$  =acceleration due to gravity,9.81m/s<sup>2</sup>;

$T_{am}$ = ambient temperature, °C

$N$ = no of fins

$K$ = thermal conductivity of material (copper)

$A$ = cross sectional area of tube

$T_{out}$ = Outside temperature

$T_{in}$ = Inside temperature

$M=\sqrt{(hp/kA)}$

$h$ = convection coefficient of air in w/ m<sup>2</sup>k

$p=\pi d$  in m

$A= \pi/4 d^2$  in m

